New Wind Energy Resource Maps of the Mid-Atlantic States

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EXECUTIVE SUMMARY

This report describes a wind-mapping project conducted by TrueWind Solutions for the US Department of Energy and a number of mid-Atlantic states. Using the MesoMap system, TrueWind has produced maps of mean wind speed and power of the mid-Atlantic region for a range of heights above ground on a 200 m grid. TrueWind has also produced data files of the predicted frequency, mean speed, and energy by direction and seasonal mean speed and power. The maps and data cover the states of New Jersey, Pennsylvania, Delaware, Maryland, Virginia, West Virginia, and North Carolina. The new wind maps provide the most complete and detailed picture of these states produced to date, supplanting the maps contained in the *Wind Energy Resource Atlas of the United States*. They should be of great assistance to both companies and individuals seeking prospective sites for small and large wind energy systems.

The MesoMap system consists of an integrated set of atmospheric simulation models, databases, and computers and storage systems. At the core of MesoMap is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model which simulates the complete physics of the atmosphere. MASS is coupled to a simpler wind flow model, WindMap, which is used to refine the spatial resolution of MASS to account for the local effects of terrain and surface roughness. MASS simulates weather conditions over the region for 366 historical days randomly selected from a 15-year period. When the runs are finished, the results are input into WindMap for the final mapping stage. In this project, the MASS model was run on a grid spacing of 2.6 km, and WindMap on a grid spacing of 200 m.

The preliminary wind maps produced by MesoMap were thoroughly validated by TrueWind Solutions in collaboration with the National Renewable Energy Laboratory (NREL). The validation process used data for 136 stations from a wide variety of sources, including airports, ocean buoys, Coast Guard stations, and towers instrumented specifically for wind resource assessment. The conclusion was that the initial wind speed estimates at 50 m height, before any adjustments, were accurate to within a standard error of about 0.3 m/s, or 6%, whereas the initial wind power estimates at 50 m height were accurate to about 40 W/m^2, or a little less than one-half a wind power class.

Qualitatively, while the preliminary maps presented an accurate overall picture of the wind resource of the region, they tended to overestimate winds in areas, such as valleys, strongly affected by nocturnal stability. We believe that the two most important sources of error are the finite grid scale of the MASS simulations (a consequence of the size of the region and limitations of budget and schedule) and the difficulty of accurately simulating the boundary layer structure under stable conditions in rough terrain.

Following the validation, the wind maps were adjusted to improve the agreement with the data, and the revised maps were reviewed once more. We avoided adjusting the maps for specific points, but rather attempted to identify and correct for patterns of error occurring over sizable regions. The speed adjustment ranged from a decrease of up to 10% to an increase of up to 7%. The power adjustments ranged from a decrease of up to 30% to an increase of up to 60%. The larger adjustments were applied only in some low-wind regions of little interest for wind energy projects.

1. INTRODUCTION

Just as the growth of the petroleum industry in the early 20th century depended on the discovery of new oil fields by prospectors and wildcatters, the growth of the modern wind energy industry – and its ability to meet growing energy needs – depends on the discovery of sites having a useful wind resource. Recognizing this need, the US Department of Energy funded in the early 1980s the creation of the *Wind Energy Resource Atlas of the United States* (Department of Energy, 1986), the first national assessment of the US wind resource.

Great strides in computers and the development of new wind resource mapping tools and methods have now made it possible to update and refine the wind resource maps contained in the US atlas. These new techniques have the potential to place vastly more information in the hands of the public, enabling anyone from major developers to individual enthusiasts to identify prospective sites for wind energy systems. Of course, mapping is just the first stage of the siting process. Promising sites identified in maps must be confirmed through field assessments and monitoring; and other hurdles such as permitting and environmental impact assessments must be overcome. Nevertheless, the availability of more detailed wind resource information should accelerate the siting process and enable more people and companies to participate in it.

The objective of this project was to create new wind resource maps and data bases of seven mid-Atlantic states (New Jersey, Delaware, Maryland, Pennsylvania, Virginia, West Virginia, and North Carolina[1]) using the latest computer tools at the highest possible spatial resolution. The wind resource data were to be produced in format that could be imported and used in a Geographcial Information System (GIS). The project had the additional aim of objectively estimating the accuracy of the maps using as much surface wind data as possible.

These objectives have been fully met. Using our MesoMap system, which was developed four years ago, we have produced new maps of the mid-Atlantic's mean wind speed and power for a range of heights above ground on a 200 m grid. We have also produced data files of the predicted frequency, mean speed, and energy by direction, as well as the seasonal characteristics of the resource.[2] The validation process provided a mechanism for objectively comparing the wind maps against data from a wide variety of sources, and for estimating the map errors, and it allowed for independent review of the maps by NREL. The final, published wind maps have been adjusted to reflect the validation findings, and consequently represents the best current estimate of the region's wind resources at a very high resolution.

In the following sections, we describe the MesoMap system and mapping process in detail; how MesoMap was applied in this project; the process by which the initial maps

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[1] The US DOE provided partial funding to map all the states except North Carolina; the rest of the funds were provided by individual state agencies. North Carolina was funded entirely by the North Carolina State Energy Office but was included in this report for completeness.

[2] The data files are provided separately on a CD-ROM.

were validated; the validation results and map adjustments; and the final wind maps and data files.

2. DESCRIPTION OF THE MESOMAP SYSTEM

The MesoMap system has three main components: models, databases, and computer systems. These components are described below.

2.1. Models

At the core of the MesoMap system is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model that has been developed over the past 20 years by TrueWind partner MESO, Inc., both as a research tool and to provide commercial weather forecasting services. MASS simulates the fundamental physics of the atmosphere including conservation of mass, momentum, and energy, as well as the moisture phases, and it contains a turbulent kinetic energy module that accounts for the effects of viscosity and thermal stability on wind shear. As a dynamical model, MASS simulates the evolution of atmospheric conditions in time steps as short as a few seconds. This creates great computational demands, especially when running at high resolution. Hence MASS is usually coupled to a simpler but much faster program, WindMap, a mass-conserving wind flow model. Depending on the size and complexity of the region and requirements of the client, WindMap is used to improve the spatial resolution of the MASS simulations to account for the local effects of terrain and surface roughness variations.

2.2. Data Sources

The MASS model uses a variety of online, global, geophysical and meteorological databases. The main meteorological inputs are reanalysis data, rawinsonde data, and land surface measurements. The reanalysis database – the most important – is a gridded historical weather data set produced by the US National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR). The data provide a snapshot of atmospheric conditions around the word at all levels of the atmosphere in intervals of six hours. Along with the rawinsonde and surface data, the reanalysis data establish the initial conditions as well as updated lateral boundary conditions for the MASS runs. The MASS model itself determines the evolution of atmospheric conditions within the region based on the interactions among different elements in the atmosphere and between the atmosphere and the surface. Because the reanalysis data are on a relatively coarse, 200 km grid, MASS is run in several nested grids of successfully finer mesh size, each taking as input the output of the previous nest, until the desired grid scale is reached. This is to avoid generating noise at the boundaries that can result from large jumps in grid cell size. The outermost grid typically extends several thousand kilometers.

The main geophysical inputs are elevation, land cover, vegetation greenness (normalized differential vegetation index, or NDVI), soil moisture, and sea-surface temperatures. The global elevation data normally used by MesoMap were produced by the US Geological Survey in a gridded digital elevation model, or DEM, format from a variety of data sources.[3] The US Geological Survey, the University of Nebraska, and the European Commission's Joint Research Centre (JRC) produced the global land cover data in a cooperative project. The land cover classifications are derived from the interpretation of Advanced Very High Resolution Radiometer (AVHRR) data – the same data used to calculate the NDVI. Both land cover and NDVI data are translated by the model into biophysical parameters such as surface roughness, albedo, and emissivity. The nominal spatial resolution of all of these data sets is 1 km. Thus, the standard output of the MesoMap system is a 1 km gridded wind map. However, much higher resolution maps can be produced where the necessary topographical and land cover data are available.

2.3. Computer and Storage Systems

The MesoMap system requires a very powerful set of computers and storage systems to produce wind resource maps at a sufficiently high spatial resolution in a reasonable amount of time. To meet this need TrueWind Solutions has created a distributed processing network consisting of 94 individual Pentium II processors and 3 terabytes of hard disk storage. Since the days simulated by a single processor are entirely independent of other days, a project can be run on this system up to 94 times faster than would be possible with any single processor. To put it another way, a typical MesoMap project that would take two years to run on a single processor can be completed in just one week.

2.4. The Mapping Process

The MesoMap system creates a wind resource map in several steps. First, the MASS model simulates weather conditions over 366 days selected from a 15-year period. The days are chosen through a stratified random sampling scheme so that each month and season is represented equally in the sample; only the year is truly random. Each simulation generates wind and other weather variables (including temperature, pressure, moisture, turbulent kinetic energy, and heat flux) throughout the model domain, and the information is stored at hourly intervals. When the runs are finished, the results are compiled into summary data files, which are then input into the WindMap program for the final mapping stage. The two main products are usually (1) color-coded maps of mean wind speed and power density at various heights above ground and (2) data files containing wind frequency distribution parameters. The maps and data may then be compared with land and ocean surface wind measurements, and if significant discrepancies are observed, adjustments to the wind maps can be made.

2.5. Factors Affecting Accuracy

In our experience, the most important sources of error in the wind resource estimates produced by MesoMap are the following:

- Finite grid scale of the simulations
- Errors in the topographical and land cover data bases

[3] The US Defense Department's high-resolution Digital Terrain Elevation Data set is the principal source for the global 1 km elevation. Gaps in the DTED data set were filled mainly by an analysis of 1:1,000,000 scale elevation contours in the Digital Chart of the World (now called VMAP).

- Errors in assumed surface properties such as roughness

The finite grid scale of the simulations results in a smoothing of terrain features such as mountains and valleys. For example, a mountain ridge that is 2000 m above sea level may appear to the model to be only 1600 m high. Where the flow is forced over the terrain, this smoothing can result in an underestimation of the mean wind speed or power at the ridge top. Where the flow is blocked by the mountains, on the other hand, the smoothing can result in an overestimation of the resource, as the model understates the blocking effect. The problem of finite grid scale can be solved by increasing the spatial resolution of the simulations but at a cost in computer processing and storage.

Winds are driven by the interaction of the atmosphere with the land surface, and thus errors in the topographical and land cover data can greatly affect the wind resource estimates. While elevation data are usually very reliable, errors in the size and location of major terrain features nonetheless occur from time to time. Errors in the land cover data occur more often, usually because of misclassification of aerial or satellite imagery. It has been estimated that the global 1 km land cover database used in the MASS simulations is about 70% accurate. Where possible, more accurate and higher resolution land cover databases are used in the WindMap stage of the mapping process to correct such errors. In the United States, a 30 m gridded Landsat-derived land cover database is used; a similar 250 m database, called CORINE, is available for Western Europe.

Even if the land cover types are correctly identified, there is uncertainty in the surface properties that should be assigned to each type, and especially the vegetation height and roughness. The forest category, for example, encompasses many different varieties of trees with varying heights and density, leaf characteristics, and other features that affect surface roughness. Likewise, an area classed as residential may consist of a scattering of single-story dwellings or a dense concentration of apartment buildings. Uncertainties like these can be resolved only by acquiring more information about the area through aerial photography or direct observation. However this is usually not practical if (as in this project) the area being mapped is very large.

3. IMPLEMENTATION OF MESOMAP FOR THIS PROJECT

The standard MesoMap configuration was used in this project. MASS was run on the following nested grids:

First (outer) grid level: 30 km
Second (intermediate) grid level: 8 km
Third (inner) grid level: 2.6 km

The 8 and 30 km grids covered the entire region. At the third grid level, 2.6 km, the region was broken up into five overlapping grids. The grid setup is shown in Map 1.

At the WindMap stage, high-resolution topographical and land cover data were used to obtain a final grid spacing of 200 m. The elevations were taken from the USGS 3-arc-second gridded topographical database of the United States, while the land cover classifications were from the USGS 30-meter gridded data set derived from Landsat imagery. Both data sets were resampled to 200 m; the elevations were resampled using bilinear interpolation, which smoothes the terrain, whereas the land cover data were first filtered to identify the most frequent land cover class within a 200x200 m area, then resampled using a nearest-neighbor algorithm. The elevation map is shown in Map 2, the land cover map (reclassified into a few representative categories) in Map 3.

Table 1 lists the categories in the land cover data base and the surface roughness values (in meters) assigned to them. The roughness map is shown in Map 4. These values were judged to be typical for each land cover class. However, the actual roughness may vary a lot within a class (except water). The roughness may also vary by season because of changes in vegetation height and leafiness as well as snow cover.

Table 1. Land Cover Classifications and Surface Roughness

Class	Description	Roughness (m)
11	Open Water	0.001
12	Perennial Ice/Snow	0.001
21	Low Intensity Residential	0.3
22	High Intensity Residential	0.75
23	Commercial/Industrial/Trans	0.01
31	Bare Rock/Sand/Clay	0.01
32	Quarries/Strip Mines/Gravel Pits	0.1
33	Transitional	0.1
41	Deciduous Forest	0.9
42	Evergreen Forest	1.125
43	Mixed Forest	1.125
51	Shrubland	0.05
61	Orchards/Vineyards/Other	0.05
71	Grasslands/Herbaceous	0.01
81	Pasture/Hay	0.01
82	Row Crops	0.01
83	Small Grains	0.01
84	Fallow	0.01
85	Urban/Recreational Grasses	0.01
91	Woody Wetlands	0.66
92	Emergent Herbaceous Wetlands	0.1

4. VALIDATION PROCEDURE

The validation was carried out in cooperation with NREL. NREL provided the bulk of the data; the rest was provided by TrueWind. A standard spreadsheet table format was followed. The table included the station name, source of data, location, anemometer height, recorded mean speed, period of record, and comments about the site such as local land cover, if available. The locations of the stations are shown in Map 5.

TrueWind then analyzed the data in the following steps for each state:

1. Duplicate stations were identified and eliminated. In a few cases it was necessary to reconcile conflicting estimates for the same station, either by picking what seemed to be the more credible of the estimates, or taking the average.
2. Station locations were then verified and adjusted, if necessary, by comparing the quoted elevations and station descriptions against the elevation and land cover

maps. Where there was an obvious error in position, the station was either moved to the nearest point of correct elevation, or if a suitable location could not be found, it was eliminated. Position errors of up to 1 or 2 km arose quite often in the older and less well-documented data sets.

3. The observed mean speed and power were extrapolated to a common reference height of 50 m using the power law. Where possible, the measured shear exponent for the site was used. In most cases, however, the shear exponent had to be estimated using information from similar locations and analysis of diurnal wind profiles and rawinsonde data. The estimated shear exponent on ridges and mountaintops ranged from 0.15 to 0.35; at airports in low-lying areas, from 0.17 to 0.23; at coastal stations, from 0.15 to 0.17; and offshore, from 0.1 to 0.14. Exceptions were made where it seemed likely the station was either unusually sheltered or the wind was strongly influenced by channeling, compression over a ridge, or acceleration down a slope.

4. The error margin of each data point was then estimated as a function of two factors: the tower height and the number of years of measurement. The tower height enters the equation because of uncertainty in the wind shear. Considering that detailed site descriptions were lacking for most stations, we assumed an uncertainty in the estimated shear exponent of 20%. In other words, if the estimated shear exponent was 0.20, the possible range (to one standard deviation) was 0.16 to 0.24.

   The period of measurement is significant because even if a site is monitored for a year or more, the resulting mean speed may not be representative of long term conditions. A rule of thumb in the wind industry is that one year of measurement will result in a mean speed that is within 10% of the long term mean with 90% confidence. This translates into a standard error of 6% for one year of data. We assumed that interannual variations are not correlated in time and are normally distributed, so that the standard error goes down in inverse proportion to the number of years (or, if climatologically corrected, the number of years of the long-term reference).

   The two uncertainties were then combined in a least-squares sum as follows:

   $$(2)\quad e = \sqrt{\left(\left(50/H\right)^{0.2\alpha} - 1\right)^2 + \left(\frac{0.06}{\sqrt{N}}\right)^2}$$

   where H is the height of the anemometer and N the number of years of measurement. For example, if the mean speed for a 10 m tower with a two-year record was 6.6 m/s, and the estimated shear was 0.14, then the estimated 50 m speed was 8.3 m/s with a standard error of 9.4%.

5. The predicted wind speed and power at each station's position were then extracted from the raw (unvalidated) maps. At first we did this using an automated GIS extraction routine, but we found that this resulted in frequent errors because of slight offsets in station locations and in the topographic and land cover data. Instead, we examined each point and extracted the most reasonable map value by

hand. This necessitated a certain amount of judgement, but we think it is more reliable than using an automated process.

6. Next, the predicted and measured/extrapolated speed and power were compared, and the map bias (map speed or power minus measured/extrapolated speed or power) was calculated for each point. Stations with especially large discrepancies (compared to the data error margin) were examined closely. In a few cases, the stations were eliminated for one of the following reasons: (a) the observed mean speed or power appeared to be grossly inconsistent with other data for similar locations in the region; (b) the data recovery percentage was very low (below 50%); or (c) the location of the station was in serious doubt.

7. The bias was then displayed in a scatterplot and on a bias map. A scatterplot allows the quick identification of outlying points and reveals the overall quality of the match between prediction and measurement. A bias map, on the other hand, is useful for revealing spatially correlated error patterns. If a cluster of stations have similar errors in sign and magnitude, it is more likely to reflect a real problem in the map than if the errors appear randomly distributed.

5. QUANTITATIVE VALIDATION RESULTS

Table 1 summarizes the results of the validation for wind speed and power. We did not compile comparable statistics for power because most of the stations did not have power data, and TrueWind did not analyze the power as closely as the speed. The table lists the number of stations retained after excluding questionable data, the mean bias (average map speed or power minus the average measured/extrapolated speed or power), the root-mean-square (RMS) discrepancy, and the estimated model error. The number of stations for which wind power data could be calculated was smaller than the number reporting mean wind speeds. The wind power error in percentage terms is larger than the wind speed error because the power varies as the cube of the wind speed.

Parameter	Number of Stations	Mean Bias	RMS Discrepancy	Estimated Model Error
Speed	136	0.23 m/s (3.9%)	0.53 m/s (8.9%)	0.34 m/s (5.7%)
Power	111	11 W/m^2 (4.4%)	49 W/m^2 (19%)	37 W/m^2 (15%)

The model error is calculated by subtracting (in a least-squares sense) the data error margin from the RMS discrepancy:

$$(3) \quad e_{MODEL} \approx \sqrt{e_{TOTAL}^2 - e_{DATA}^2}$$

This equation assumes that the model and data errors are both normally distributed and independent of one another. The model error is a more realistic estimate of the accuracy of the map as it accounts for the fact that some of the apparent discrepancy between the map and data is caused by errors in the data.

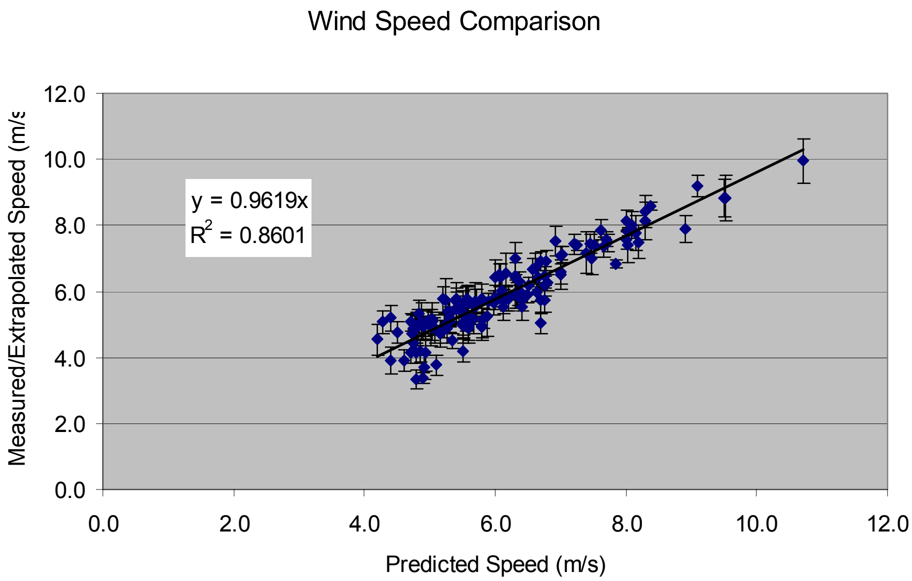

Figure 1. Scatter plot of predicted and measured/extrapolated mean wind speed at 50 m height for 136 stations in the mid-Atlantic region. Vertical error bars reflect uncertainty in the extrapolated data due to limited tower heights and periods of measurement.

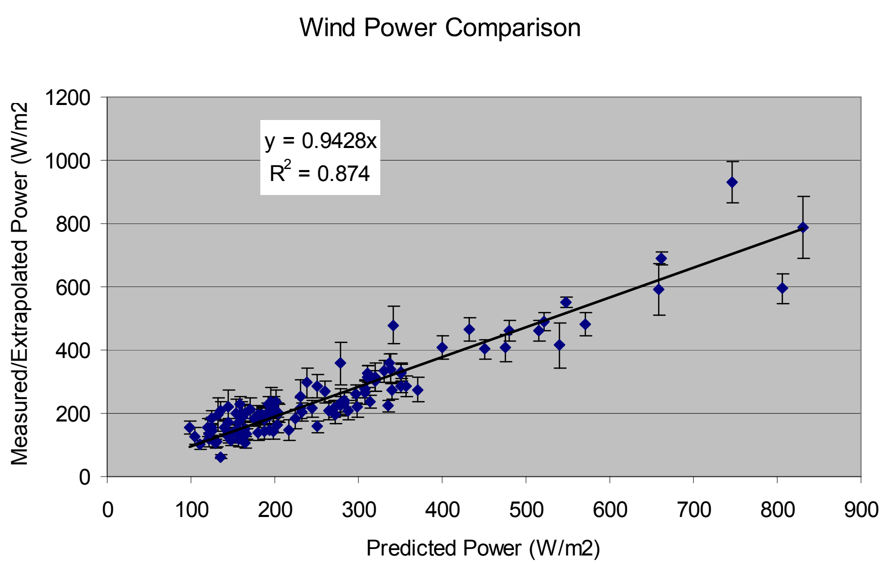

Figure 2. The same as Figure 1, but showing mean wind power at 111 stations.

The scatterplots in Figures 1 and 2 compare the predicted and measured-extrapolated mean wind speed and power at 50 m height. The error bars were calculated with Equation 2. The linear trend line, which is forced through the origin, indicates that the predicted speed and power were on average slightly higher than the measured/extrapolated speed and power (i.e., the slope of each line is less than one). Nevertheless the r^2 regression coefficient is very high, indicating that the predictions explain the great majority of the variance in the observed wind resource. Furthermore, the bias does not appear to vary significantly with speed or power.

6. QUALITATIVE OBSERVATIONS AND SOURCES OF ERROR

It is clear from the foregoing results that the overall pattern of the wind resource in the preliminary maps was reasonably accurate. If our estimates of the uncertainty in the data are in the ballpark, then roughly half of the scatter between the predicted and measured/extrapolated wind speed and power was caused by the data. Some of the remaining scatter is probably due to particular conditions around the stations that are not known or cannot be resolved by the model. For example, a tower may have been situated in the shadow of building or next to a stand of trees, resulting in a lower measured wind resource; or it may have been on an especially well exposed outcropping, resulting in a higher resource. Errors in the elevation and surface roughness data used by the model are another possible explanation.

However, the validation also revealed some clear patterns suggesting possible limitations in the model. First, there was a tendency for the model to overestimate the wind resource in valleys and low-lying areas, particularly where the data indicate the atmosphere is strongly stable at night.[4] This was especially true in the southern part of the region west of the Appalachian and Blue Ridge mountains. In a typical pattern, the observed wind speed would drop sharply at night, whereas the simulated wind speed would remain higher. A similar problem appeared along the coast south of the Chesapeake Bay. Both problems suggest there may be a weakness in the model's treatment of the thermally stable nocturnal boundary layer. Under some conditions, it appears that the model may allow too much energy to be transferred through the boundary layer to the surface. This issue is the subject of research at TrueWind.

The second significant pattern was that the predicted wind shear on mountaintops, particularly in the southern part of the region, was too low, resulting in an overestimation of winds near the surface. We received multi-level wind data for several mountaintop sites and found the wind shear exponent ranged from 0.25 to 0.35 at heights up to about 50-70 m, whereas the predicted shear at this level ranged from 0.10 to 0.20. The relatively high observed shear is indicative of an internal boundary layer created by the abrupt transition from free-air flow to a tree-covered mountaintop. The MASS model is run at too coarse a scale – 2.5 km – to capture this effect, which occurs over a distance of tens to hundreds of meters, while the simplified equations used in Windmap may be defeated by the complexity of the situation. An additional consideration is that rolling terrain, which is characteristic of much of the region west of the Applachians, induces drag on the atmosphere, creating higher wind shear than would be predicted from surface roughness alone. While the equations in MASS can simulate such "form drag," the terrain seen by the model is smoothed out to some degree, making it likely that the effect is underestimated.

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[4] Thermal stability refers to the buoyancy of the air. At night, as the land cools, the air near the surface becomes less buoyant, resulting in less friction with the air above it. This in turn tends to increase the shear and lower the wind speed.

7. ADJUSTMENTS TO THE WIND MAPS

After reviewing the validation results, TrueWind and NREL jointly proposed and agreed on a number of adjustments to be made to the maps. The adjustment factors for speed and power are shown in Figure 3. The final speed or power is calculated by multiplying the initial speed or power by one plus the corresponding adjustment factor. The adjustment is assumed to be the same for all heights and seasons.[5] In reality, the map error may vary with both season and height above ground, but since the data were not validated on a seasonal basis or at different heights, we used the same adjustment.

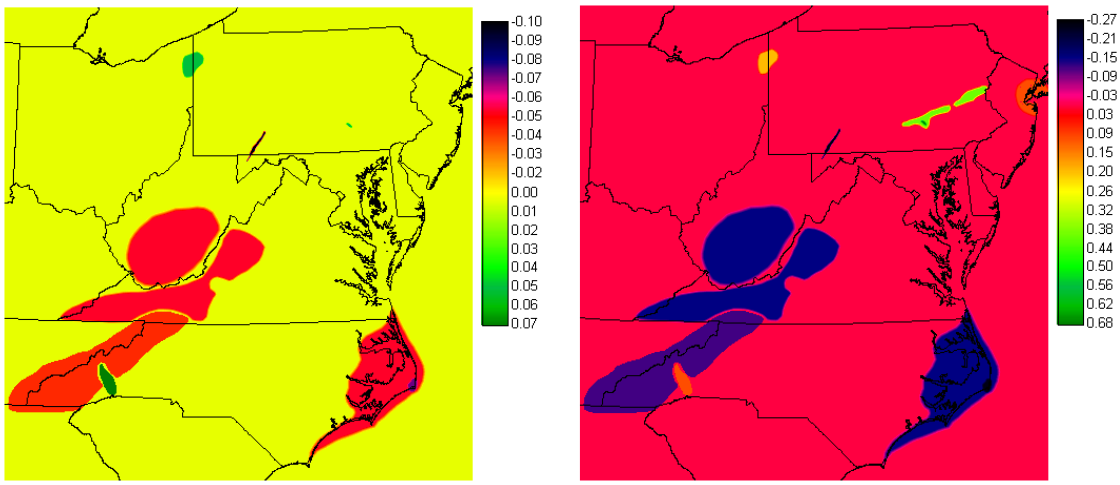


Figure 3. Wind speed (left) and power (right) adjustment factors. The final wind speed or power equals the initial (raw) model output multiplied by one plus the corresponding adjustment factor. Note the different color scales.

The speed adjustment ranged from a decrease of up to 10% to an increase of up to 7%, while the power adjustment ranged from a decrease of 27% to an increase of 68%. The power adjustments tend to be larger because of the cubic relationship between speed and power; however a strict cubic relation was not applied to the adjustments in all cases. Reductions occurred in southern West Virginia, western Virginia, western North Carolina, and coastal North Carolina. Increases occurred over limited areas of Pennsylvania and the Asheville valley of western North Carolina.

8. FINAL WIND MAPS

Maps 5-8 show the final mean wind speed at 30, 50, 70, and 100 m, and Map 9 the final mean wind power at 50 m. The map height is relative to the effective ground level. In dense forest, the effective ground level is defined as the canopy height, which is typically about 2/3 the height of the tree tops. For example, if the tree height is 15 m (45 ft), the effective ground level is about 10 m (30 ft) above the true ground, and a map height of 50

[5] An exception was made in the mountains of western North Carolina, where the wind shear exponent below 70 m was increased so that the adjustment at 50 m was 0.96, whereas the adjustment at 30 m was 0.88.

m therefore corresponds to a height of 60 m above the true ground. CD-ROMs containing GIS-compatible wind resource data files, both seasonal and annual, for all states are provided separately. Instructions for the use of the data are provided on the CD-ROMs and in Appendix II.

The mean speed and power describe different aspects of the wind resource, and both can be useful in different ways. The mean speed is the easiest for most people to relate to and is consequently the most widely used. However, it does not directly measure the power-generation potential in the wind. The mean wind power, which depends on the air density and the cube of the wind speed, is regarded by some experts as a more accurate indicator of the wind resource when assessing wind project sites. Generally speaking, commercial wind power projects using large turbines require a mean speed of at least 7 m/s at 70 m height or a mean power of at least 400 W/m^2 at 50 m height (NREL class 4). Small turbines are designed to operate at lower wind speeds, and may be useful at mean speeds at 30 m height as low as 5-6 m/s (approximately NREL class 2 to 3).

The maps show that the wind resource of the mid-Atlantic states is concentrated in two main areas: the Appalachian Mountains (and its neighboring ranges, the Allegheny Mountains and the Blue Ridge) and the coasts or offshore. While it is not immediately apparent at this scale, the resource along many ridgelines is excellent (NREL class 4-7) and could support a number of large wind energy projects. The coastal resource is not as good, but may still be attractive especially on exposed points and islands; offshore wind projects are a possibility. In general, the mountain resource decreases as one moves south, whereas the coastal resource increases. The former is because the mountaintop winds are highest in winter, and winter storms cross the northern part of the region more often than the southern. The coastal resource, on the other hand, is enhanced by summer storms, which affect the south more often than the north. The resource in most low-lying areas is relatively poor through the region, mainly because of extensive tree cover, which exerts friction on the atmosphere and reduces the near-surface wind speeds.

It should be emphasized that the mean wind speed or power at any particular location may differ substantially from the predicted values, especially where the elevation, exposure, or surface roughness differs from that assumed by the model, or where the model scale is inadequate to resolve significant terrain features. Furthermore, the map height should be interpreted as the height above the vegetation canopy. In dense forests with tall trees, the actual height above ground at which the predicted winds would be observed may be as much as 10-15 m higher than the nominal height.

Detailed guidelines for using the maps and adjusting the wind resource estimates where necessary are provided in Appendix II.

The following sections present brief summaries of each state.

8.1. Delaware

The wind maps show that inland Delaware has a class 1 wind resource, with mean wind speeds at 70 m of 5.5-6 m/s. With few hills to speak of, the state must look to its coastal and offshore resource. Coastal winds average class 2-3 (6-7 m/s), increasing to class 3-4 (7-8.5 m/s) offshore, particularly on the Atlantic side.

8.2. Maryland

Much of Maryland has a class 1-2 wind resource, with mean wind speeds at 70 m of 5.5-6.5 m/s. Where hills and mountains protrude high enough above the landscape, however, the wind is stronger, and the resource is predicted to reach class 4-6, or 7-8 m/s. The hills in western Maryland concentrate the wind resource exceptionally well because they are oriented perpendicular to the prevailing westerly and northwesterly winter winds. The threshold elevation at which the wind resource becomes attractive for large wind projects in western Maryland appears to be about 550-600 m.

The wind resource in central Maryland is moderate, but it improves near the coast. Offshore, especially on the Atlantic side, the wind resource is predicted to reach 7.5-8.5 m/s at 70 m, or NREL class 4-5.

8.3. New Jersey

New Jersey as a whole has a class 1 wind resource with mean wind speeds at 70 m of less than 6 m/s. Like Delaware, most of New Jersey is quite flat, with few hills rising sharply enough above the surrounding terrain to be exposed to significant winds. The best hilltop winds are expected to be found in extreme northern New Jersey, where class 3 winds (6.5 m/s at 70 m) may occur elevations above 400 m.

The wind resource improves near the coast. Barrier islands as well as exposed points such as Cape May are predicted to have a class 3 resource; in places it may reach class 4 (7 m/s or higher at 70 m). Offshore the wind resource improves further, with winds of class 4 and 5 (7-8 m/s) predicted within 10 kilometers of the shore.

8.4. North Carolina

North Carolina as a whole has a class 1 wind resource with mean wind speeds at 70 m of less than 5.5 m/s. Aside from the frictional effect of trees, the state is far enough south to frequently escape the winter storm track that crosses the mid-Atlantic and northeastern states. The mountains of western North Carolina are nonetheless predicted to have an excellent wind resource in many locations because the mountains tend to compress and accelerate the wind forced over them. A good example is Grandfather Knob, which at 1770 m (5800 ft) is one of the highest mountains in the area, and on which the both the observed and predicted mean speed at 50 m is about 10 m/s (class 7). At the same time, multi-level measurements taken on a few peaks in the region have shown that the wind speed at typical monitoring heights of 10 to 30 m is often dramatically reduced by the frictional effects of trees and taller peaks upwind. The wind shear is consequently higher than usual on exposed mountaintops. It appears that this high-shear layer quickly fades above 50 m, and thus we expect the map values to be most accurate at the 70 m and 100 m levels than at the lower levels.

Generally speaking, mountain peaks in North Carolina must be at least 1100 m (3600 ft) high to have a very good wind resource. One exception may be the mountains at the outlet of the Asheville valley, such as Sugarloaf and Laurel, which are around 800-1000 m (2600-3300 ft) high, or 200-400 m (650-1300 ft) above the valley floor. The valley appears to form a channel for cold air flowing out of the Appalachians, which increases the wind resource on high points within and just outside the valley.

The coastal wind resource of North Carolina is also good. On the barrier islands and exposed points along the mainland shore, it is predicted to reach class 3-4, with typical mean speeds of 6.5-7.5 m/s at 70 m. The resource improves considerably offshore, away from the frictional effect of the land, resulting in a class 4-6 power and 70 m speeds of 7.5-8.5 m/s.

8.5. Pennsylvania

The wind resource of this state is concentrated in the hills of south-central and northeastern Pennsylvania, where mean wind speeds are predicted to be highly suitable for large wind projects. A good example is the ridge just east of Meyersdale, where the 70 m wind speed is predicted to exceed 8 m/s in places. The threshold elevation for acceptable wind speeds appears to be around 650-700 m (2100-2300 ft). This relatively low elevation range and generally more moderate terrain suggests that a greater number of sites may be developed in Pennsylvania than in states to the south. Pennsylvania has no coastal resource, however, aside from the class 2-3 winds predicted along the Lake Erie shore.

8.6. Virginia

Like other states in the region, the wind resource of Virginia is class 1 overall. The Appalachian Mountains and Blue Ridge of western Virginia are however predicted to have an excellent wind resource in many locations. An example is Whitetop Mountain in extreme southwestern Virginia, with an elevation of 1680 m (5500 ft), and where the observed and predicted mean speed at 70 m exceeds 9 m/s (class 7).

The elevation at which the mountaintop wind resource becomes attractive for wind projects in Virginia increases from about 400 m (1300 ft) in the north to about 1100 m (3600 ft) in the south. An exception to the pattern may be the mountains at the outlet of the Roanoake valley, such as Roanoake Mountain and Windy Gap, which at a height of 500-800 m (1600-2600 ft) are well below the elevation that would be expected to have good winds in this part of the state. The valley, like Asheville valley in North Carolina, appears to form a channel for cold air flowing out of the mountains.

The coastal wind resource of Virginia is not as good as the mountain resource but still offers possibilities. On islands and exposed points along the mainland shore, the wind power is predicted to reach class 3, with typical mean speeds of 6-7 m/s at 70 m. The resource improves considerably offshore, resulting in a class 4-5 power and 70 m speeds of 7-8 m/s.

8.7. West Virginia

The mountains of eastern and especially northeastern West Virginia are predicted to have an excellent wind resource. A good example is the ridgeline stretching from Cabin Mountain to Snowy Peak along the border of Tucker and Grant counties, where the 70 m wind speed is predicted to reach or exceed 9 m/s (class 6-7). The threshold elevation for acceptable wind speeds appears to be around 900 m (2900 ft) in the northeastern part of the state; in the southeast, the necessary elevation is somewhat higher, around 1100 m.

9. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

We have successively used the MesoMap system to predict the wind resource in the mid-Atlantic region at a high spatial resolution. Maps and databases have been produced for several heights above the effective ground level (forest canopy or ground). The maps point to a number of promising wind resource sites in the Appalachian Mountains and neighboring ranges as well as along the coast and offshore. The preliminary map estimates correlated well with data obtained for 266 towers and extrapolated to a height of 50 m, indicating that the method overall is sound. The scatterplot of measured and predicted wind speed exhibited a strongly linear relationship, with a slight positive bias, and a r^2 regression coefficient of over 85%. The map standard error in speed, without adjustments, was estimated to be 0.34 m/s, or 5.7%. This level of error is comparable to the uncertainty in one year of data taken at 50 m height, with no climatological adjustment. Based on the validation, the preliminary maps were adjusted in places by amounts ranging up to 10% in speed and 68% in power. The end result, we believe, is more accurate than the validation statistics indicate; however this cannot be established objectively without additional data.

While the maps produced in this project have been shown to be quite accurate, we have identified several areas that merit further research or data collection:

1. High-resolution modeling of selected areas. Many of the windiest locations are in mountainous terrain, which could not be modeled as accurately as might be wished at the 2.5 km grid scale of the MASS simulations. Higher resolution model runs could help refine the wind resource estimates in promising areas.
2. Analysis of boundary layer issues. The stability of the nighttime boundary layer can have a substantial impact on the wind resource – for example, by suppressing valley winds and enhancing winds on bluffs – and yet it poses a significant modeling challenge. A focused program of research on improved methods for simulating the stable atmosphere could substantially improve the accuracy of the wind map in areas of promise of wind development.
3. Improved definition of land cover and surface roughness. Uncertainty in the height and density of trees, among other aspects of land cover, increases the uncertainty in wind resource estimates on forested ridgelines and other locations. There is undoubtedly much data and human expertise on the types and characteristics of the forests and other land cover types of the mid-Atlantic states which could not be brought to bear. A study to synthesize such information and apply it to wind energy assessment would be desirable.
4. Measuring the wind aloft. Most of the towers which provided data for the validation of the maps were less than 10 m in height. Lack of knowledge of the wind shear consequently introduced a large uncertainty in the measured wind resource at the hub height of wind turbines. New measurements using taller towers in promising yet unexplored areas are certainly called for. However, even the current generation of 50 m towers do not reach the hub height of modern turbines, which is typically 70 or 80 m, let alone the tops of their blades, which may reach 130 m. Sodar, a tool for measuring the vertical wind profile to heights of 200 m or more, can provide valuable additional information at a moderate cost.

In addition to exploring the wind resource at a particular site, sodar could be very useful in validating and refining models to simulate the boundary layer, with benefits in other areas being mapped.

APPENDIX I: GUIDELINES FOR USE OF THE MAPS

The following may be useful guidelines for interpreting and adjusting the wind speed estimates in the maps, especially in conjunction with the accompanying CD-ROMs (one for each state). The CD-ROMs allow users to obtain the "exact" wind speed value at any point on the map, and it also provides the elevation and surface roughness assumed by the model, which are needed to apply the adjustment formulas given below.

1. The maps assume that all locations are free of obstacles that could disrupt or impede the wind flow. "Obstacle" does not apply to trees if they are common to the landscape, since their effects are already accounted for in the predicted speed. However, a large outcropping of rock or a house would pose an obstacle, as would a nearby shelter belt of trees or a building in an otherwise open landscape. As a rule of thumb, the effect of such obstacles extends to a height of about twice the obstacle height and to a distance downwind of 10-20 times the obstacle height.
2. Generally speaking, points that lie above the average elevation within a 200×200 m grid cell will be somewhat windier than points that lie below it. A rule of thumb is that every 100 m increase in elevation will raise the mean speed by about 0.5 m/s. This formula is most applicable to small, isolated hills or ridges in flat terrain.
3. The roughness of the land surface – determined mainly by vegetation cover and buildings – up to several kilometers away can have an important impact on the mean wind resource at a particular location. If the roughness is much lower than that assumed by the mapping system, the mean wind speed will probably be higher. Typical values of roughness range from 0.01 m in open, flat ground without significant trees or shrubs, to 0.1 m in land with few trees but some smaller shrubs, to 1 m or more for areas with many trees. These values are only indirectly related to the size of the vegetation; they are actually scale lengths used in meteorological equations governing the structure of the boundary layer.

   An approximate speed adjustment *in the direction of the roughness difference* can be calculated using the following equation:

$$\frac{v_2}{v_1} \approx \frac{\log\left(500/z_{01}\right)}{\log\left(h/z_{01}\right)} \times \frac{\log\left(h/z_{02}\right)}{\log\left(500/z_{02}\right)}$$

   v_1 and v_2 are the original and adjusted wind speeds at height h (in meters above the effective ground level), whereas z_{01} and z_{02} are the model and actual surface roughness values (in meters). As an example, suppose the land cover data used by the model showed an area to be forested in all directions with an estimated roughness value of 1 m, whereas in fact the land was fairly open in all directions with an estimated roughness value of 0.1 m. For h = 65 m, the above formula gives

$$\frac{v_2}{v_1} \approx \frac{\log\left(500/1\right)}{\log\left(65/1\right)} \times \frac{\log\left(65/0.1\right)}{\log\left(500/0.1\right)} = 1.13$$

implying the model wind speed should be increased by about 13%.

This formula assumes that the wind is in equilibrium with the new surface roughness above the height of interest (in this case 65 m). When going from high roughness to low roughness (such as from forested to open land), the clearing should be at least 1 km wide for the benefit of the lower roughness to be fully realized. However, when going from low to high roughness, the reduction in wind speed may be felt over a much shorter distance. For this and other reasons, the formula should be applied with caution. Where doubts arise, users are urged to obtain the advice of a qualified consulting meteorologist.

APPENDIX II: THE DATA CD-ROM

Each CD-ROM accompanying this report contains a free program called ArcExplorer 2, produced by ESRI, which allows users to view, query, copy, and print the state maps in an interactive environment. This addendum contains basic instructions for using the ArcExplorer program and associated maps and data bases. For detailed instructions, see the ArcExplorer on-line help file or visit www.esri.com/software/arcexplorer/index.html. The CD-ROM contains additional data files not used by ArcExplorer which may be imported into ArcInfo, ArcView, or other GIS programs. These files are described at the end of this addendum.

The data in each CD-ROM are referenced both to latitude and longitude and to ground coordinates. The projection and datum for the ground coordiantes vary depending on each state's longitude and special requirements:

Maryland and Delaware: Universal Transverse Mercator (UTM) coordinate system, zone 18, WGS84 datum.

North Carolina, Virginia, and West Virginia: UTM zone 17, WGS 84 datum.

Pennsylvania: State Plane coordinate system, northern zone.

New Jersey: State Plane coordinate system.

Regardless of projection, all ground coordinates in the data files are in meters.

9.1. Using Arcexplorer

STEP 1. SYSTEM REQUIREMENTS AND INSTALLATION

The first step is to install the ArcExplorer program on your system. According to ESRI, the maker of ArcExplorer, ArcExplorer 2 works on Windows 98/2000/NT operating systems. However, users report that it also works on Windows 95 and Windows Me operating systems. Because of the large data files, it is recommended that you have at least 128 MB of RAM.

Execute the program called ae2setup.exe found on the CD-ROM root directory. The setup program will guide you through the rest of the process. The data files can be left on the CD-ROM, but if you have room, you should copy the data directories to your hard disk. That will give you much faster performance.

STEP 2. OPENING THE PROJECT

Start ArcExplorer either by clicking on the icon that was placed on your Desktop (if you chose that option during installation) or by choosing Start - Programs - ESRI - ArcExplorer.

Choose File - Open and navigate to the CD-ROM or to the directory where you placed the files. Open the project file (extension: AEP).

NOTE: The file may take several minutes to load, especially from CD.

STEP3. FINDING YOUR WAY AROUND THE MAIN SCREEN

After ArcExplorer finishes loading the project, you should see the main window with a color wind map resembling the maps presented in this report. You may adjust the shape of the window to fit the map by dragging on its corners or sides. Notice that below the main map the X and Y position of the mouse pointer (in meters in UTM or state plane coordinates) is shown, along with the scale of the map and a scale bar.

A small Overview Map may be visible in the lower left corner of the main window. As you zoom in on an area in the main map, you will see a red rectangle on the Overview which shows where you are.

MAP LAYERS

Look to the left of the map window. Here you see a legend with the names of each of the map layers (also called themes). Not all of the layers are visible on the map when you first open the project. Some will appear only when you zoom sufficiently far into the map. Typically the first two layers have _ROSE and _MAIN in their names. They are described below:

<u>XX_ROSE</u>. This layer contains wind rose data including the frequency, mean speed, and percent of total wind energy from each of 16 directions (starting due north clockwise around the compass). The points are displayed only at high magnification (see below for instructions on changing the magnification).

<u>XX_MAIN</u>. This layer is the main wind resource database. It contains the mean annual speed, wind power, and Weibull frequency distribution parameters. The points are displayed only at a high magnification.

Most of the other layers contain overlays such as rivers, roads, and county or state boundaries. The last few layers are bitmap images (called something like SPD50.BMP) which is used as a color backdrop for the other layers. The color bands are defined in 0.5 m/s increments; for a legend, see the maps provided at the end of this report.

Now look along the top of the main window where a number of icons are visible. Aside from Open, Close, Save, and other standard functions, several useful tools are found here. To find out what each one does, hold the mouse pointer over the icon for a couple of seconds and a description will appear.

Starting from the left on the second row of icons, verify the locations of the following tools: Zoom to Active Theme, Zoom In, Zoom Out, Identify, and Measure. Following is a brief description of each:

Zoom to Active Theme. This tool is very useful for restoring the map to its full (initial) size after zooming. A theme (map layer) is activated by clicking on its name in the legend on the left.

Zoom In and Zoom Out. These tools function just like they do in many other programs. After selecting the tool, the mouse looks like a magnifying glass. Each click of the magnifying glass within the main map increases or decreases the scale by a factor of two. If you click and drag the magnifying glass over an area, you will zoom directly to that area.

Pan (hand tool). This tool allows you to move the map around by clicking on it and dragging in any direction. You can also navigate by clicking on the red rectangle in the overview map and dragging it where you want to go. This can be especially useful when you are at high magnification.

Identify. This tool is used to get more information about features you select on the map. You will find it most useful for querying the wind speeds and other data in the MAIN and ROSE layers. To use the tool, first select a map layer by clicking on the name in the legend on the left. Then click on the icon and the mouse pointer will change to an "i" with a circle around it. Click on a feature in the selected map layer and a data table will appear. If features are close together, the data table may contain entries for several of them.

Measure. This tool is used to measure distances on the map. To use it you will first have to select a measurement unit (kilometers, meters, miles, or feet) by clicking on the small arrow to the right of the icon. After selecting the tool, click on the map at one point and drag to another and the distance "as the crow flies" will be displayed.

STEP 4. ZOOM AND DATA TABLES

Select the Zoom In tool and click several times anywhere on the map. Or you may find it easier and quicker to select a zoom area by clicking and dragging the pointer to form a rectangle. In any case, once the scale becomes small enough, a number of blue points and red circles should appear. Each point represents one data point in the MAIN layer. The circles represent points in the ROSE layers.

First select the MAIN theme by clicking on its name in the legend to the left of the map. You will notice that as you pass the mouse over the points in the map, a number will appear next to the mouse pointer. This is the mean speed (in m/s) at each point.

Now select the Identify tool and click on one of the points. A data table will appear showing the exact X and Y coordinates (in meters UTM), the latitude and longitude in decimal degrees, the elevation and roughness assumed by the model (both in meters), the mean speed, power, and the Weibull C and k factors. At first the field names will be listed in a mixed-up order. Click on the word Field at the top of the list and the field names will be alphabetized.

Close the data table and select the ROSE layer. Click on a circle and alphabetize the data table. The fields labeled FREQ 1...FREQ16 correspond to the frequency (in percent) from each direction of the compass. The fields SPEED 1...SPEED16 are the mean speeds for each direction (normalized to the average), and the POWER 1...POWER16 fields are the percent of total energy for each direction.

Note that in a 16-sector wind rose, each sector corresponds to the following direction ranges (in degrees from north):

Sector	*Degree Range*
1	348.75 - 11.25
2	11.25 - 33.75
3	33.75 - 56.25
4	56.25 - 78.75
5	78.75 - 101.25
6	101.25 - 123.75
7	123.75 - 146.25
8	146.25 - 168.75
9	168.75 - 191.25
10	191.25 - 213.75
11	213.75 - 236.25
12	236.25 - 258.75
13	258.75 - 281.25
14	281.25 - 303.75
15	303.75 - 326.25
16	326.25 - 348.75

If you want the data points and circles (or any of the other features) to appear at a different magnification, then go to the magnification level you want using the zoom in and out tools. Right click on the name of the layer and select Set Maximum Scale. If you zoom out from that scale, the layer will disappear. If you prefer to set the display manually each time, then select Remove Scale Factors. Then, to prevent the map layer from displaying at any scale, simply uncheck the box next to the theme name.

The symbols used in the map overlays can be changed by going to Theme Properties. Select a map layer, then choose Tools - Theme Properties from the menu.

STEP 5. SAVING, COPYING AND PRINTING MAPS

Once you have selected an area of interest, you can copy the map to the Windows clipboard or save it as a picture file (bmp or emf format) by selecting commands under the Edit menu. Or you can print it by selecting Print under the File menu.

Be warned that the maps produced directly from ArcExplorer are not of very high quality. To produce a better map, consider saving the wind map as a bmp or emf file and importing it into a graphics program, or using the bitmap images as backdrops in a GIS program such as ArcView, ArcInfo, or Idrisi.

STEP 6. FOR MORE INFORMATION

If you have questions about the ArcExplorer program, please see the on-line documentation under the Help menu, view the ArcExplorer manual in PDF format on the CD-ROM, or visit http://www.esri.com/software/arcexplorer/index.html. For help with or information about the data base or any other aspect of the wind maps, send an e-mail to mbrower@truewind.com.

9.2. Other Data Files on the CD-ROM

The other data files on the CD-ROM contain additional information or are in different formats for different applications. The directories are as follows:

BMP. This directory contains the bitmap images used as a backdrop in ArcExplorer. The BMP files are accompanied by ESRI "world files" which provide geographic referencing when used in a compatible program such as ArcView.

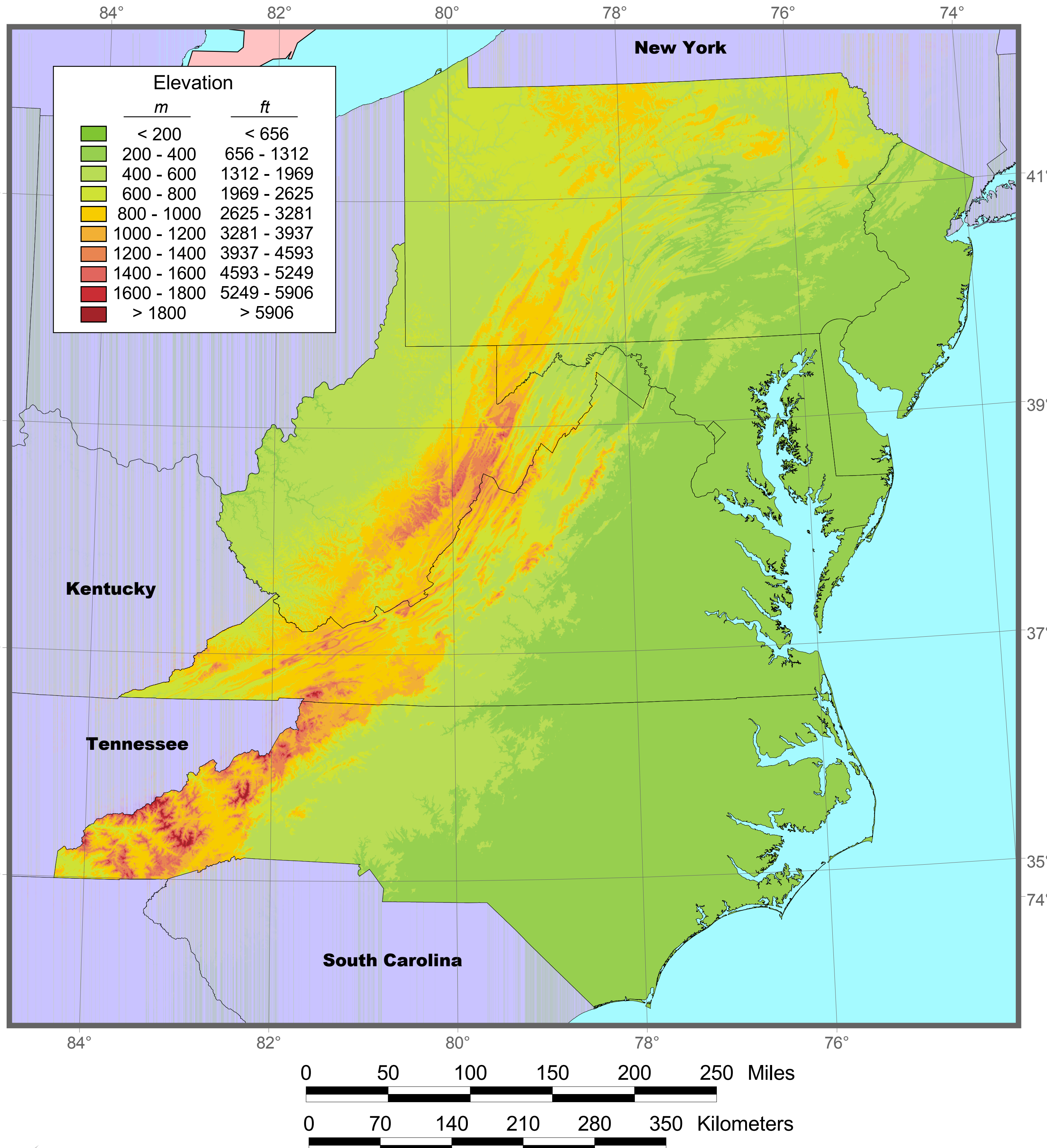
CSV. The files named XX_MAIN.CSV are comma-delimited databases containing, for each grid point, the X and Y coordinates, latitude and longitude, the assumed (model) elevation and roughness, the predicted wind speed and wind power data at each height, and Weibull distribution parameters C and k at 50 m. The files named XX_ROSE.CSV contain the wind rose frequencies, mean speeds, and percent of energy. There is one file of each type for the annual data and one file of each type for the seasonal data. The XX_MAIN data are on a 200 m grid, the XX_ROSE data are on a 2 km grid. The files can be easily imported into a database program such as Microsoft Access, or they can be used to create Shape files or other GIS overlay files in ArcView or ArcInfo.

FloatingPoint. The files in this program are ArcInfo-type floating point grid files containing the mean wind speed and power at each height. They can be imported into ArcView or ArcInfo and may be more convenient than using the CSV files. However only annual data are provided in this format.

Raster. These files provide an alternative bitmap-type format for use in compatible GIS programs. The format is recognized by ArcView and ArcInfo. However no wind speed or power data can be read directly from them – they indicate only the wind speed or power class, as shown in the wind maps.

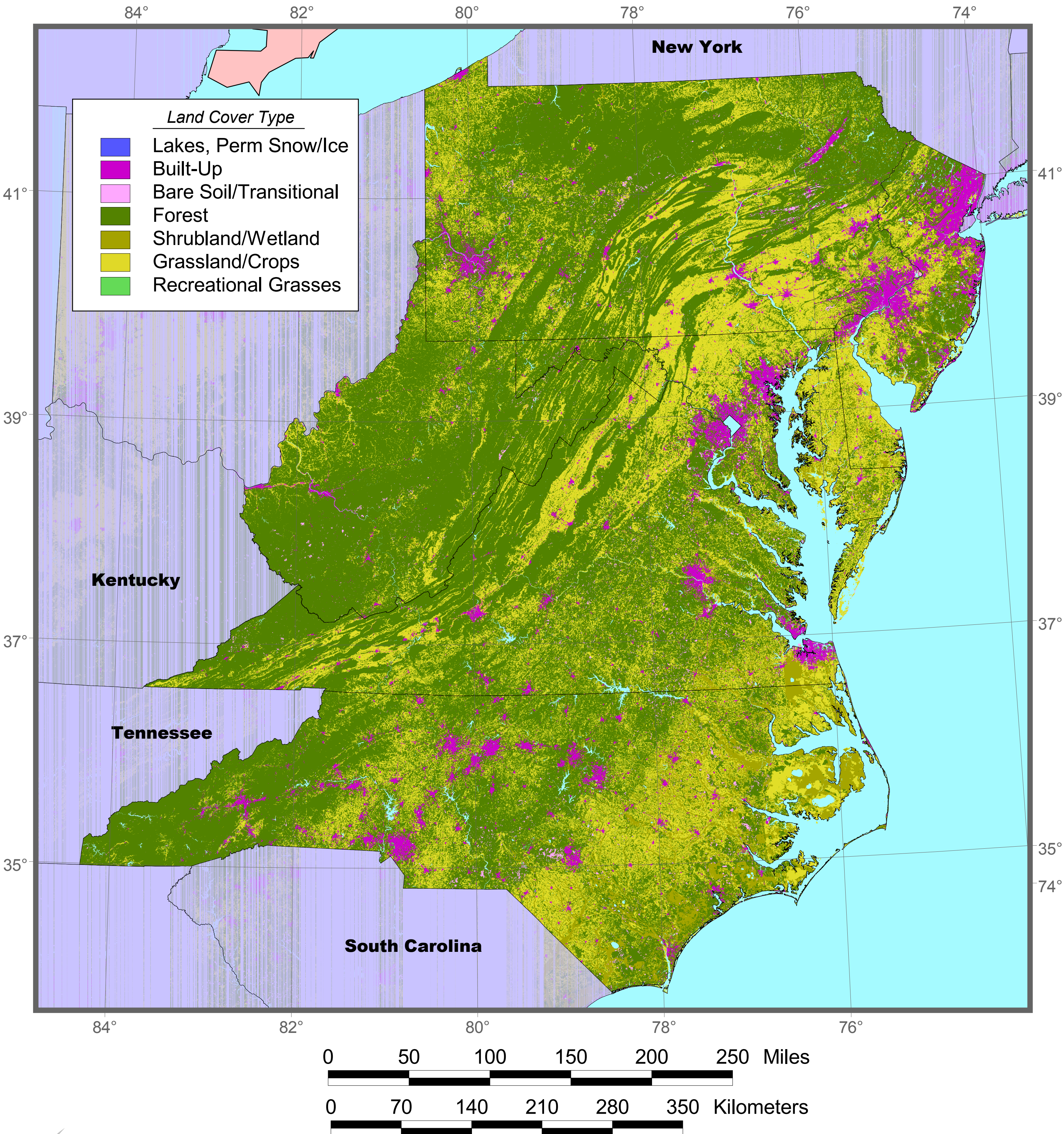
Shape Files. These are the vector overlays used in ArcExplorer. They can be also be used in ArcView and ArcInfo, and they can be imported into many other GIS programs. Included among them are the annual XX_MAIN and XX_ROSE shape files used in the ArcExplorer project included on the CD-ROM.

Map 1. Elevation



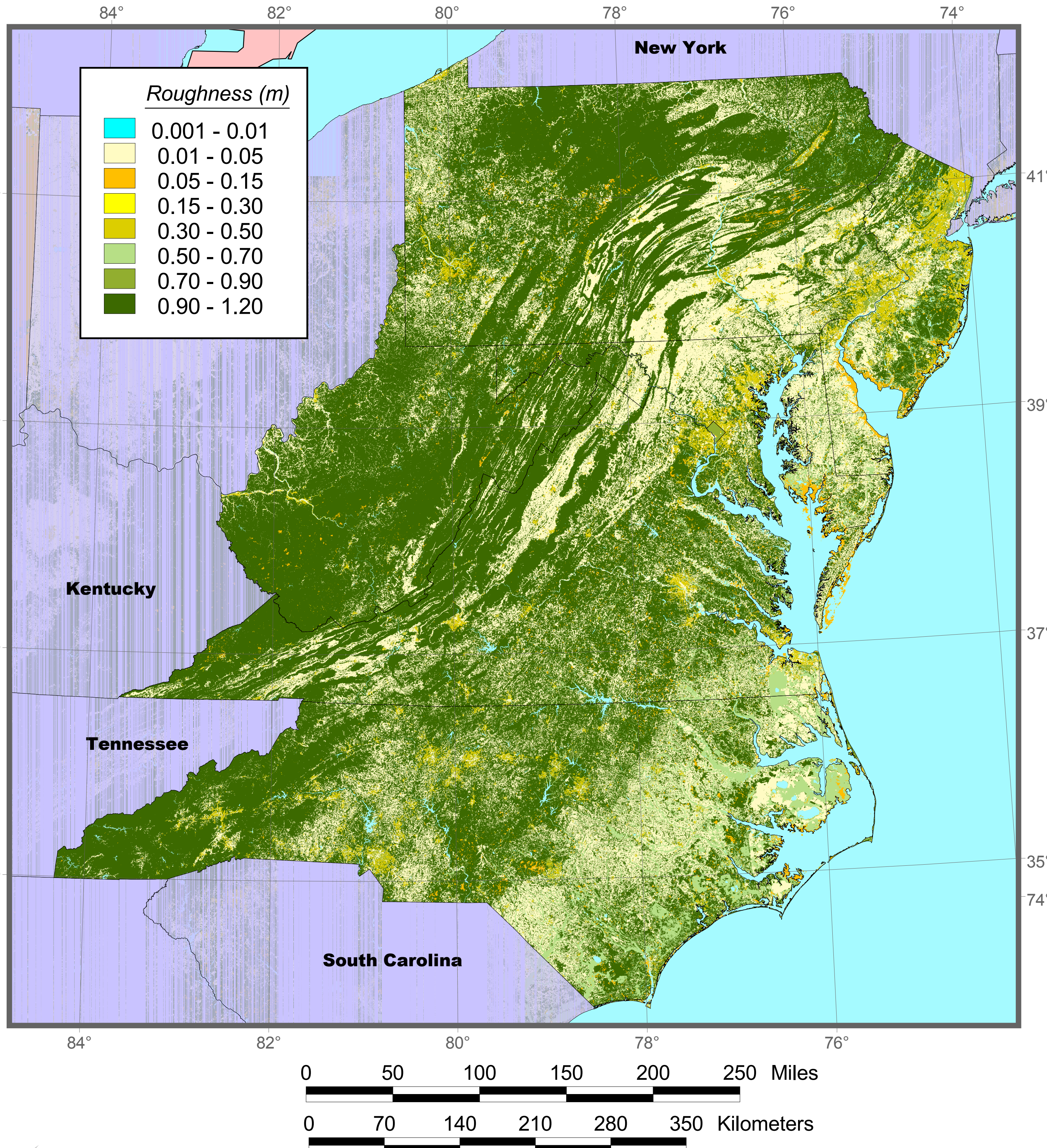
TrueWind Solutions

Map 2. Land Cover



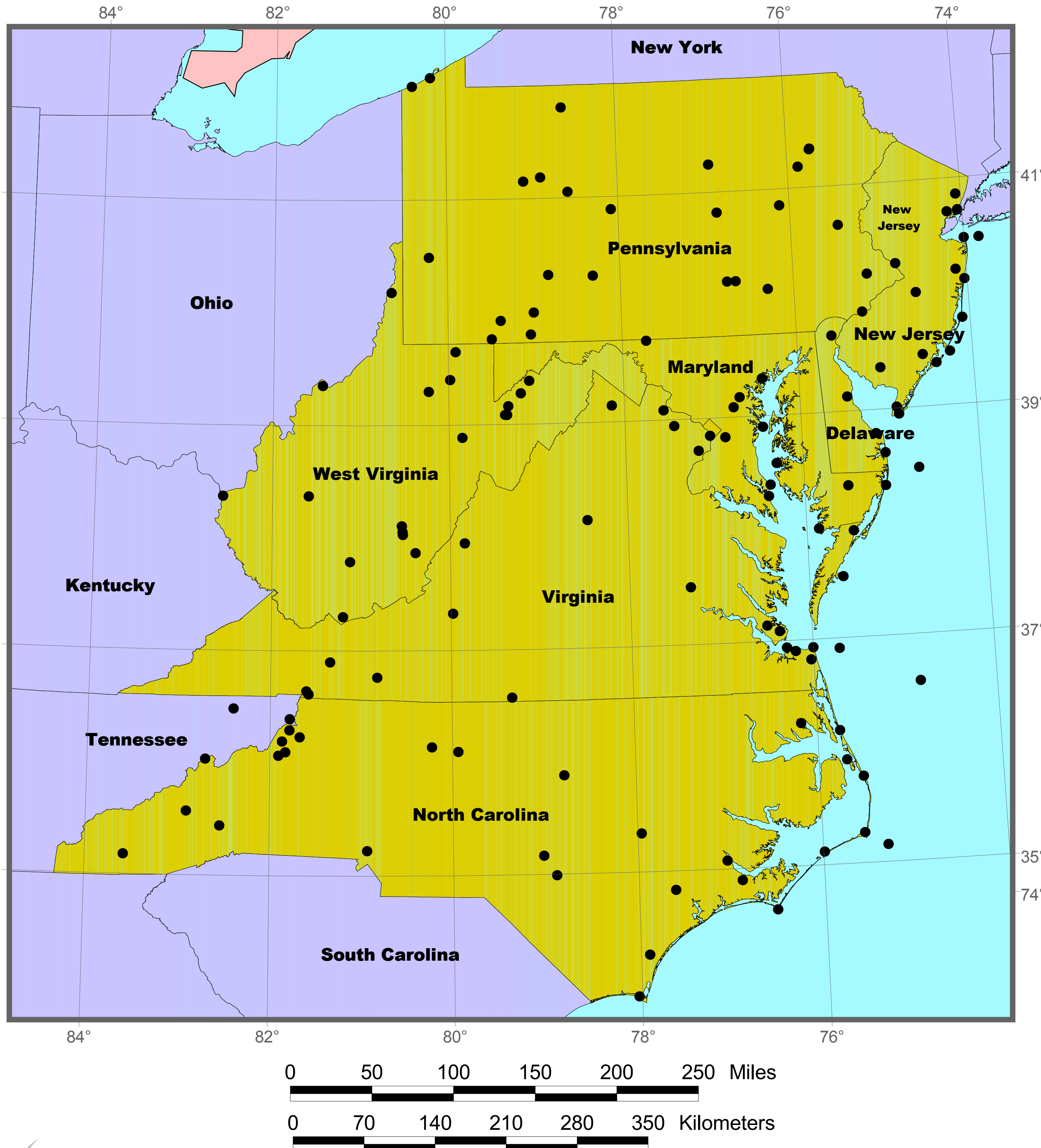
TrueWind Solutions

Map 3. Surface Roughness



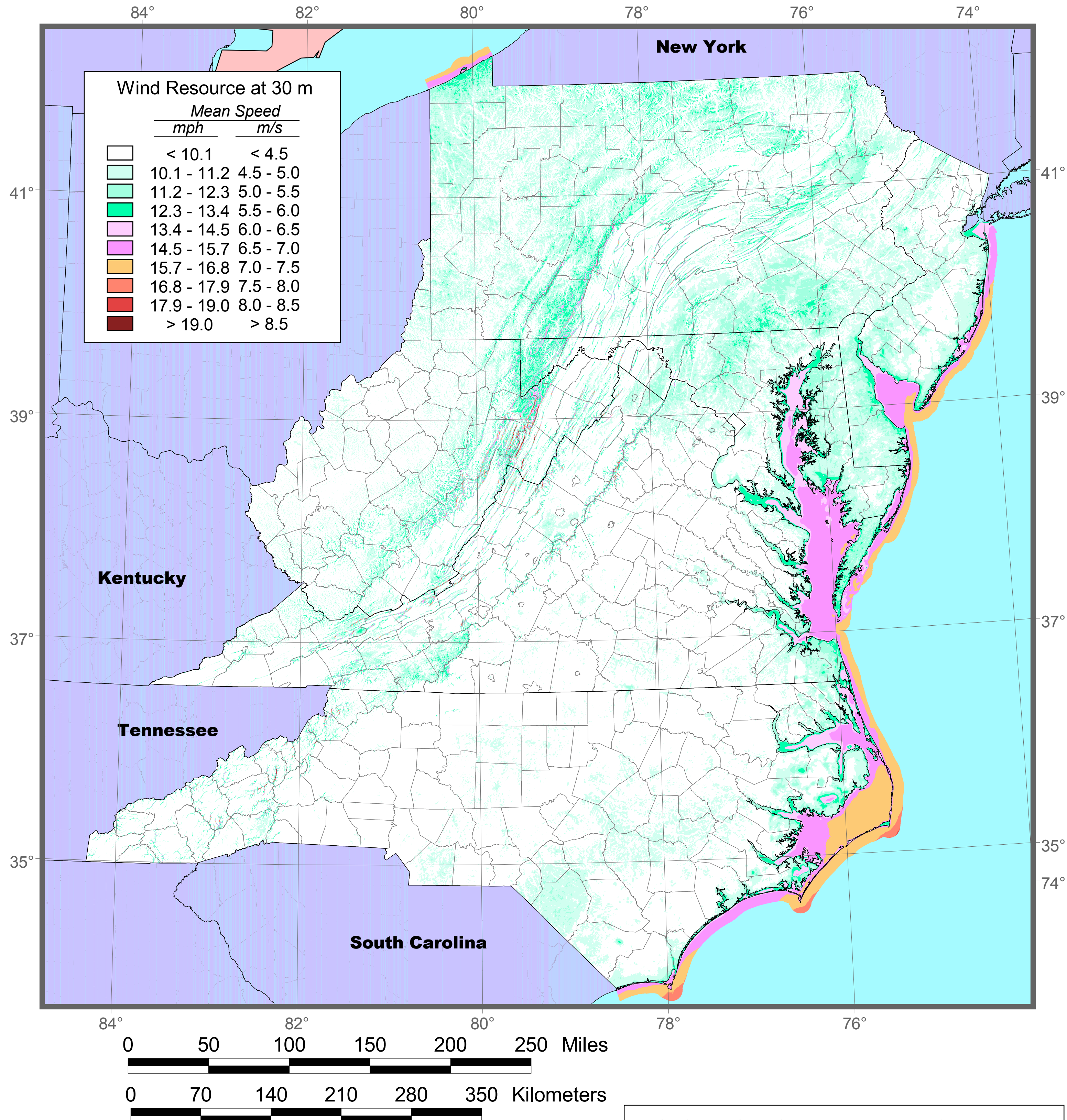
TrueWind Solutions

Map 4. Validation Sites



TrueWind Solutions

Map 5. Wind Speed at 30 m

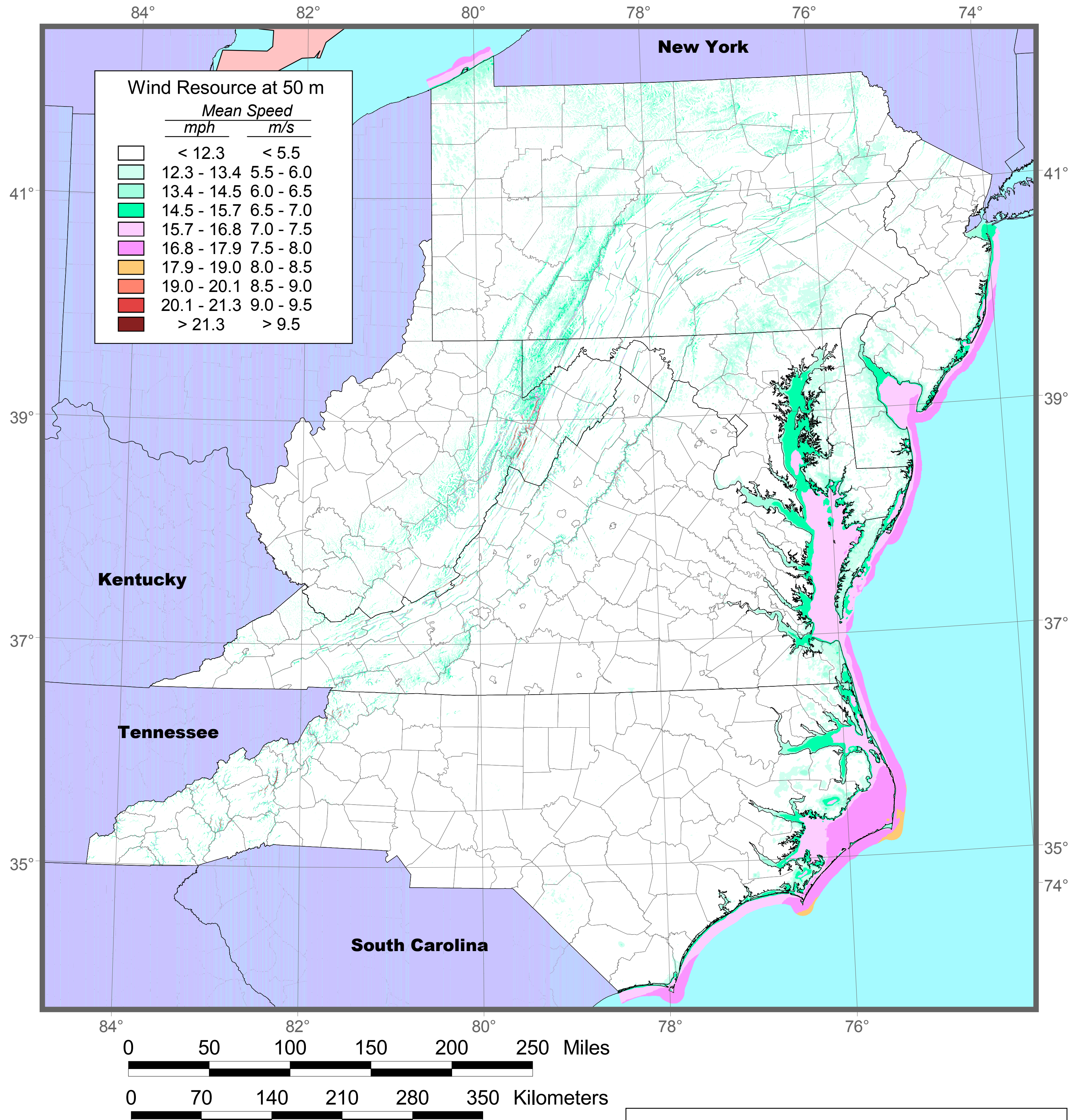


Projection: Universal Transverse Mercator (Zone 17)
Spatial Resolution of Wind Resource Data: 200 m

This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

TrueWind Solutions

Map 6. Wind Speed at 50 m

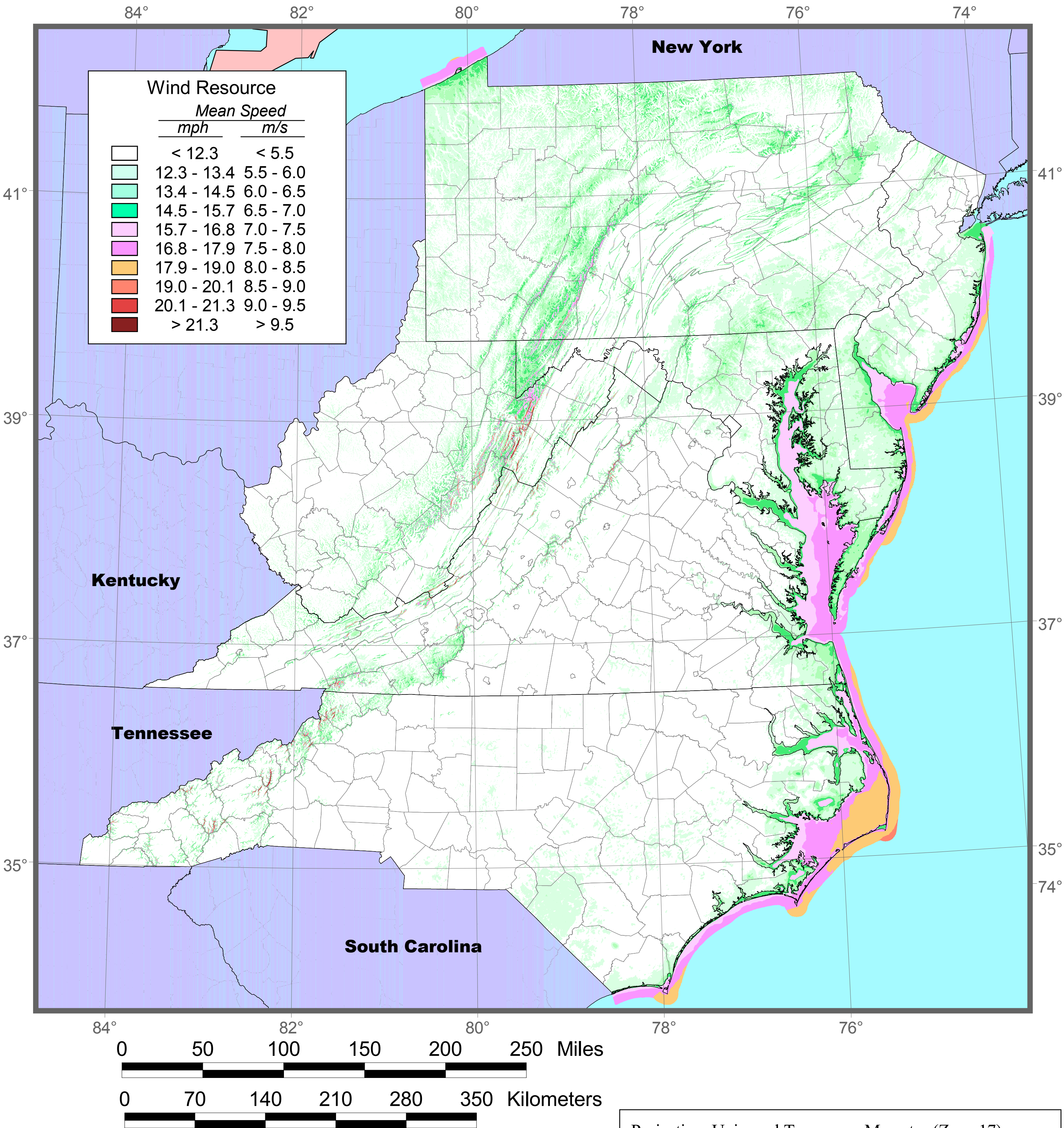


Projection: Universal Transverse Mercator (Zone 17)
Spatial Resolution of Wind Resource Data: 200 m

This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

TrueWind Solutions

Map 7. Wind Speed at 70 m

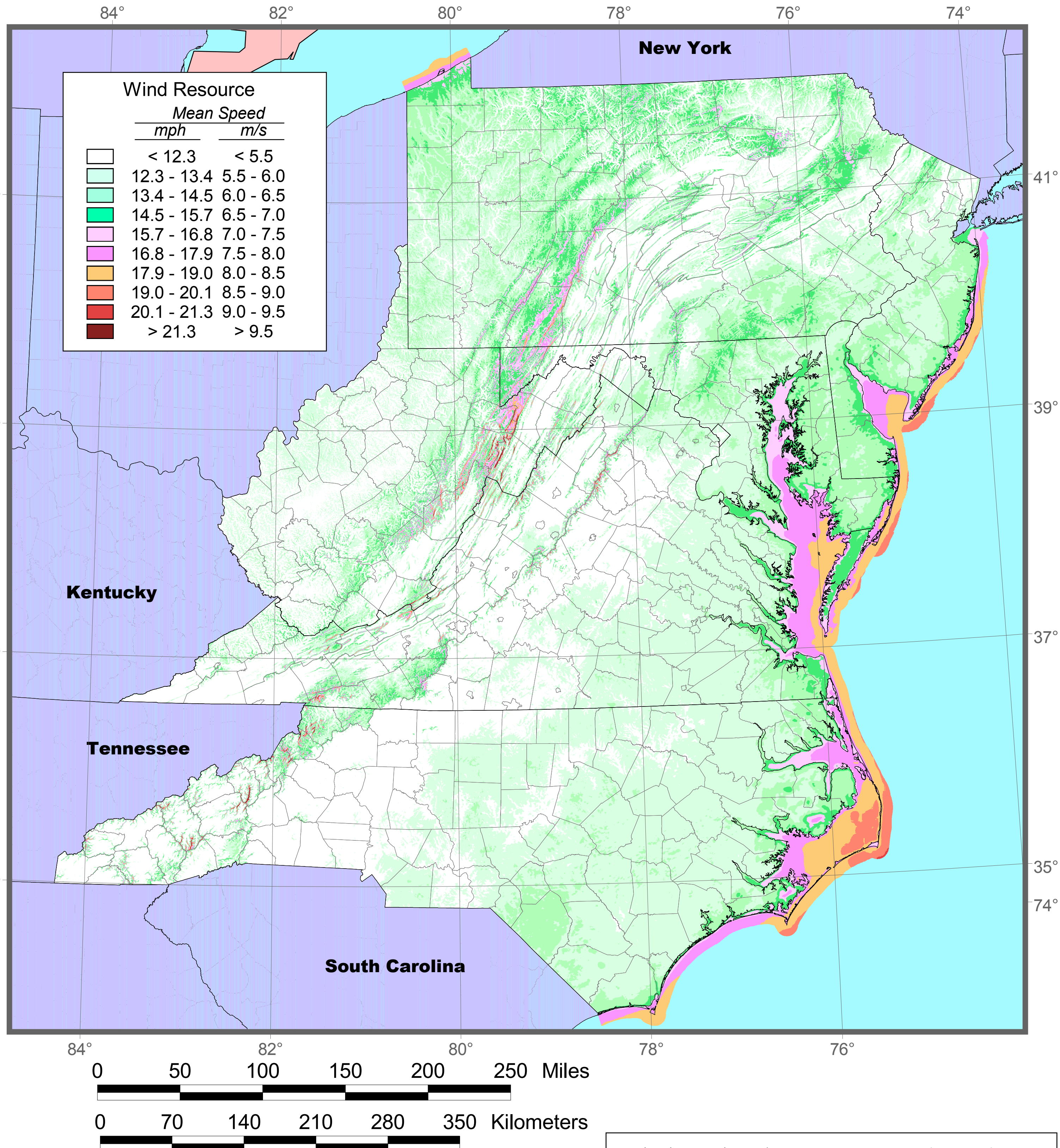


Projection: Universal Transverse Mercator (Zone 17)
Spatial Resolution of Wind Resource Data: 200 m

This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

TrueWind Solutions

Map 8. Wind Speed at 100 m

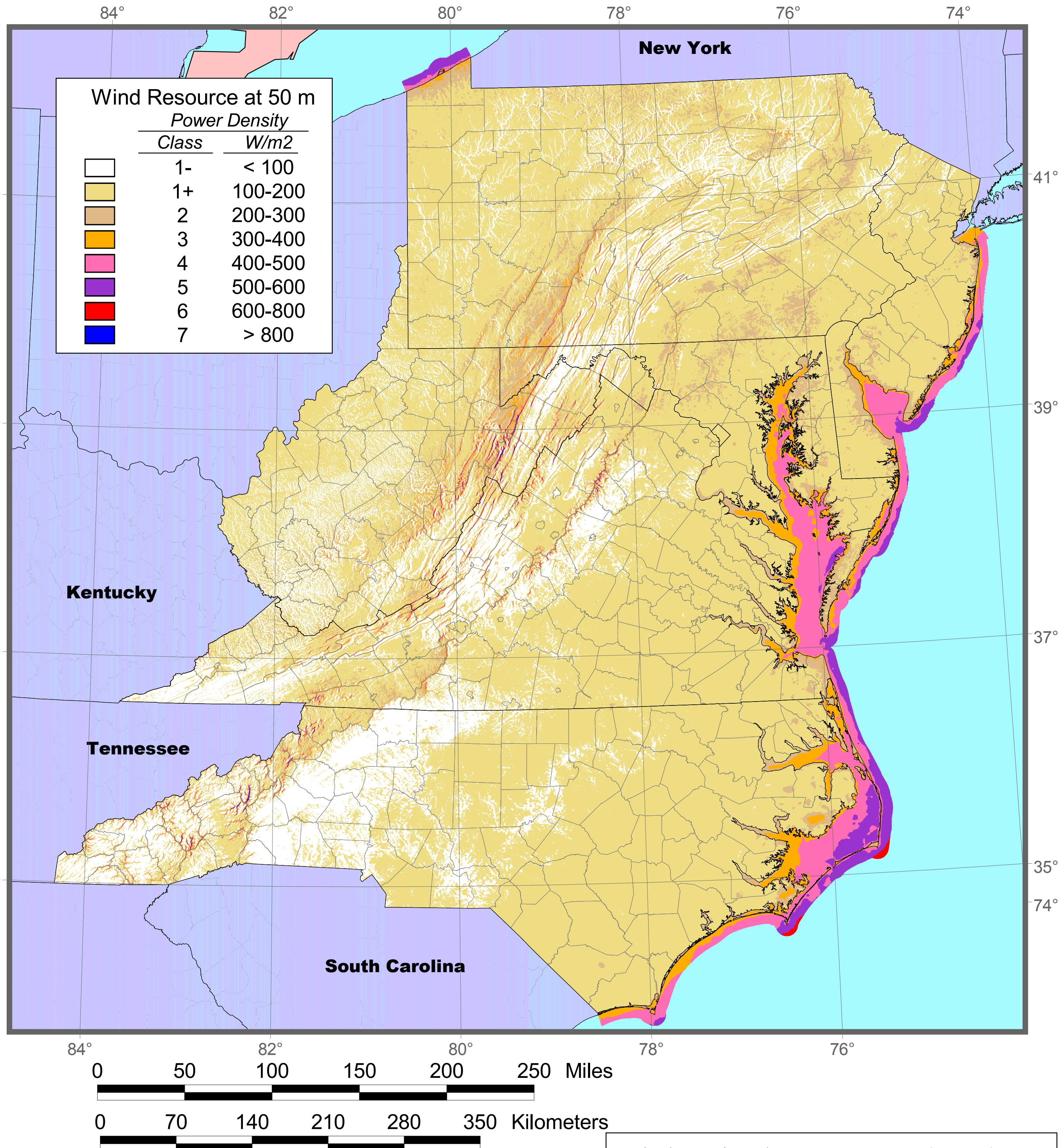


Projection: Universal Transverse Mercator (Zone 17)
Spatial Resolution of Wind Resource Data: 200 m

This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

TrueWind Solutions

Map 9. Wind Power at 50 m



TrueWind Solutions

Projection: Universal Transverse Mercator (Zone 17)
Spatial Resolution of Wind Resource Data: 200 m

This map was created by TrueWind Solutions using the Mesomap system and historical weather data. Although it is believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.